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On Integrated Product Architectures: Representation, modelling and evaluation

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Abstract

Continued growth in the commercial aerospace industry makes aircraft manufacturers look for low maintenance, fuel efficient airplanes and aircraft engines are an important factor in the maintenance and fuel costs. The drive for operating cost reduction leads to innovative engine architectures that can place very different requirements on supplier provided components. The suppliers will then need to understand and predict consequences on their components and sub systems following the new system architectures proposed. Insights they get about the consequences of engine architecture changes help them to be prepared for future developments.

This research presents two aspects of the behaviour of aero engine static components from a supplier: (1) the behaviour of the component as a whole in the system and (2) the internal organisation of the component so that the behaviour required of it is achieved by the system. System in this context refers to the aero engine. The component is integrated in that multiple functions are satisfied by one single structure. Studies in the first aspect provide a measure of the sensitivity of the whole engine to component designs. The studies also present an initial framework to perform such system-component interaction investigations. Studies in the second aspect provide a way to organise functions and means for an integrated architecture product so that the internal organisation is better understood and can be subjected to evaluations.

Preliminary results show that the influence of the supplier component on system level operations cannot be neglected. The framework to evaluate system level effects of supplier component design needs further refinement with better fidelity models at all levels considered. With respect to the internal organisation of components, a method now exists to isolate, organise, represent and analyse design information of integrated components, taking into consideration different manufacturing options. Continued studies will focus on functional and physical domain decomposition of the component reliably and objectively so that alternative product architectures for the component can be evaluated and appropriate design and manufacturing decisions can be made.

Keywords: Integrated product architecture, system-component interaction, product internal organisation, functional decompositions

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Appended Publications

Paper A: Raja, Visakha., Isaksson, Ola. "Generic Functional Decomposition of an Integrated Jet Engine Mechanical Sub System Using a Configurable Component Approach". 22nd ISPE Inc. International Conference on Concurrent Engineering, CE 2015, TU Delft, Netherlands, 20-23 July 2015 Vol. 2 (2015), p. 337-346.

Work distribution

Raja conceptualised and wrote the paper. Isaksson functioned both as a contributor and reviewer.

Paper B: Raja, Visakha., Samuelsson, Sebastian., Isaksson, Ola., Grönstedt, Tomas. "Exploring Influence of Static Engine Component Design Variables on System Level Performance". 22nd International Symposium on Air Breathing Engines, ISABE2015. October 25-30, 2015, Phoenix, Arizona, Paper No 20082.

Work distribution

Raja and Samuelsson conceptualised and wrote the paper. Isaksson and Grönstedt functioned both as contributors and reviewers.

Paper C: Raja, Visakha., Johannesson, Hans., Isaksson, Ola. "Describing and evaluating functionally integrated and manufacturing constrained products". Submitted to Research in Engineering Design, on 14 June 2016.

Work distribution

Raja conceptualised and wrote the paper. Johannesson contributed to the CC theory and functioned as a reviewer. Isaksson functioned both as a contributor and reviewer.

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1 Introduction

Due to the global nature of business and the general rise in wealth, the number of people who fly is increasing steadily around the world. A Boeing market outlook (Boeing, 2015) reports an additional 150-170 million passengers in 2014 to the 3.1 billion total passengers of 2013. Consequently commercial aerospace industry also grows which needs more fuel efficient airplanes that lead to innovative engine designs. Older and time tested engine architectures undergo step changes or further design improvements on existing design so that efficiencies are improved. The same aircraft may have different engine options with either option taking a different route to efficiency improvements. For example, for the Airbus A320NEO[1] aircraft, two engine options are available. The engines are delivered by Pratt & Whitney Commercial Engines as well as CFM International Aero Engines. Both engines are based on two shaft architecture though the Pratt & Whitney engine uses a gear box to rotate the intake fan slower which is claimed to reduce the fuel burn. The engine by CFM on the other hand uses existing architecture but proposes design improvements and technology infusions to individual modules so that similar gains in efficiency are achieved. It need not be step changes or design improvements to existing architecture to improve the engine performance. It can also be that advanced architectures like open rotors (Clean Sky, 2016) are proposed by the OEM's (Original Equipment Manufacturers). Irrespective of how the engine manufacturers improve their engines, the drive for betterments will be reflected with the component suppliers. Thus, suppliers need to ensure that their designs fit a wide range of engine architectures.

In contrast to a common product development lifecycle, where requirements are developed at the beginning and are more or less fixed during the remaining part of the lifecycle, requirements arise throughout the lifecycle for a commercial aircraft engine (Hague, 2001). The component might need to have an increased load carrying capacity, stringent restrictions could be placed on flow losses through the component and it might need to have a much reduced weight. For significantly different engine architectures, the interfaces of the supplier's component might change resulting in entirely different product designs at the supplier's end. Changes throughout the lifecycle of the product leave the supplier with limited time and design leeway to respond to OEM's requests. For instance, after an engine test, the loads on the supplier's component could be very different from the initial set of loads which was used to finalise the product geometry. The new set of loads might make the geometry not meet structural requirements for the product. If the component that is to be supplied is of considerable size, design analyses might span multiple disciplines (structural, aero-thermo and fluid flow analyses for example) and design evaluations consume additional time. All these factors make it necessary to predict future requirements on the products that a supplier manufactures. Business intelligence needs to be supplied with realistic engineering results so that correct decisions are made.

A number of measures are adopted in the industry to manage consequences due to late or continuous changes in customer requirement. Concurrent or integrated engineering are often suggested. In addition to the adoption of appropriate product development practices, the

[1] NEO stands for Next Engine Option; http://www.airbus.com/presscentre/hot-topics/a320neo/; [28 April 2016]

suppliers themselves could try to make their components robust for changes. To do this, it is necessary that the supplier understands the working of their product in the system that they supply to (in this case, the system is simply the aero engine) as well as how it is that the product meets requirements arising from the system.

For a component supplier, analysis capability is often limited to the components they manufacture. Knowledge exists inside the company about the component as far as the design and production is concerned. On a sub-system and component level, main focus is to understand the loads and constraints from the system. Knowledge of how the system (aero engine) operates and possible future developments and consequent implications for system architectures is available through university partnerships. For an aero engine, this involves performing thermodynamic analyses so that the propulsive characteristics of the engine are evaluated. Thus the type of analyses performed on a system level and component level are different and if it is desired to understand the effects of system level changes on the component, reliable engineering measures should be developed.

This licentiate work is part of a project (VINNOVA-NFFP6, 2013) that aims to develop engineering measures so that a company will be better informed and prepared for future developments. The company here is GKN Aerospace Sweden AB and the project is a close collaboration among GKN, product and production development department at Chalmers and the applied mechanics department at Chalmers. This licentiate work is done as an industrial PhD student at the product and production development department at Chalmers.

1.1 Research context

A jet engine is typically referred to have a ‘cold’ section and a ‘hot’ section. Cold section includes principally the components located before the combustor of the engine (where the temperature of the engine is comparatively lower) which are not exposed to combustion gases. Hot section encompasses all components in contact with the combustor, through the turbine and engine exhaust, and consequently exposed to high temperature combustion gasses. The structures that GKN designs and manufactures belong to two major classes, cold and hot structures, depending on where these structures are located in the engine. Figure 1 shows the location of cold and hot structures in an aero engine and figure 2 shows a generic cold and a generic hot structure.

Throughout the thesis, the term structures can mean both cold as well as hot structures. Additionally, the terms component and product are also used to refer to the structures. The structure is a component in an engine while it is one of the products of the supplier. This thesis has the supplier’s view and therefore the term product is used frequently to refer to the structures. Multiple functions are satisfied by one single structure thereby making these structures what is called ‘integrated architecture’ products.

The behaviour of the structures in the entire engine and the organisation of the structures themselves are the focus of the project. Current methods to predict the behaviour of structures are based on engineering simulations structured in a design of experiments (DOE) or optimisation framework. Organisation of the structure is considered in design theoretical terms, staring with functional decompositions. The present work has thus two fronts, a systems engineering, multi-disciplinary design and optimisation front (which evaluates the behaviour of the structure as a whole, in the system) and a design theoretical front (which helps with product architecture and internal organisation of an integrated product)

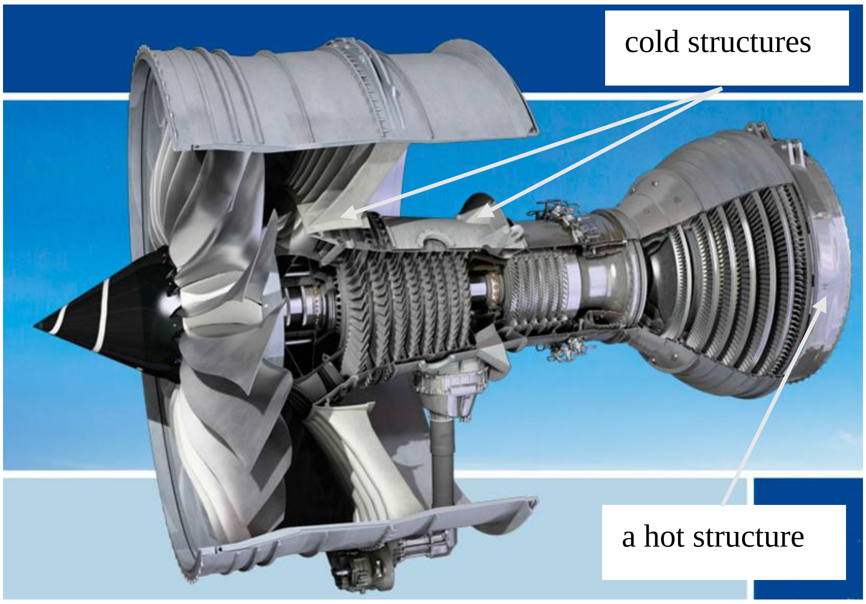

Figure 1 A Rolls Royce Trent 1000 engine (Rolls-Royce plc, 2014). Locations of cold and hot structures are marked in the figure.

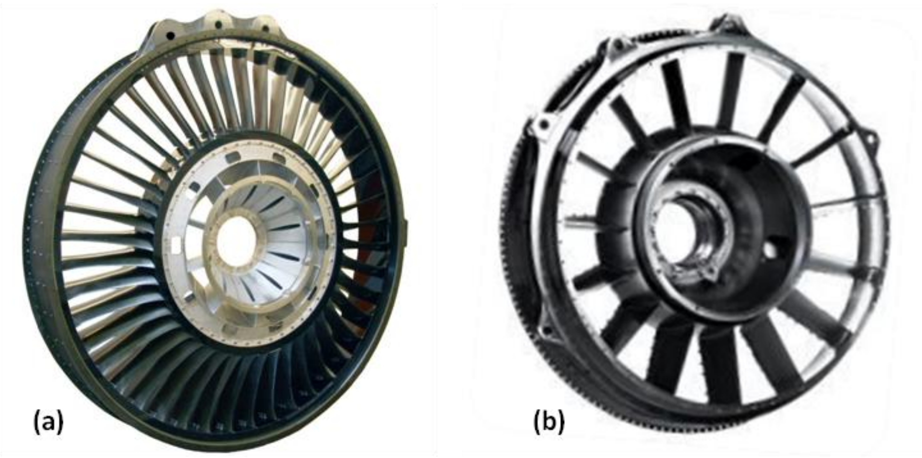

Figure 2 Generic cold and hot structure (GKN Aerospace, 2014); (a) is a mid frame and (b) is a turbine rear structure. Figures do not correspond to structures marked in figure 1.

1.1.1 Research questions

To model and assess engine components and sub systems that fit into alternative engine architectures, there is a need to better understand how component dimensions and deformations are affected by changes in Engine Architecture and installation (VINNOVA-NFFP6, 2013). Referring to the project, the research question is stated as below:

> ***RQ:*** *How are component dimensions and deformations affected by changes in Engine Architecture and installation?*

Certain keywords emerge from the research question which are (a) component dimensions (b) component deformations (c) engine architecture and (d) engine installation. As the research project is done onsite at GKN, this work limits itself to aspects of the RQ concerning keywords (a) and (b) only, specifically, *the effects on component dimensions and deformations*. Changes in engine architecture and installation are treated as inputs for the studies concerning effects on components. Calculations for evaluating engine architecture changes in itself is a PhD project, run parallel with the work presented here, at the applied mechanics division of Chalmers University of Technology (Samuelsson, 2016).

To facilitate the understanding of the effects on the component, an analysis framework (an outline or coordinating methodology) should exist to observe the functioning of the component in the system. Also, better understanding of the component, in terms of how well it satisfies the functions intended of it should also be created. Thus the research should focus in two directions, one that concentrates on the functioning of the component as a whole in a system and another which concentrates on the individual areas of the component. In view of these observations, the RQ can be split to two:

RQ1: *How does the product behave in the system?*

RQ2: *How does the product adapt to the system?*

In both RQ1 and RQ2, *Product* refers to the structures that are under consideration, the cold and hot structures discussed previously (refer part 1.1) while *system*, refers to the complete aero engine.

Referring to *RQ1*, quantitative measures of the product's performance in the system is sought. The product is considered as a whole. To obtain a measure of the product's performance in the system (behaviour), coupled disciplinary studies will need to be performed and newer frameworks need to be specified to perform the studies. It may also be necessary to perform simplifications of the component so that only the most sensitive information is coupled back and forth.

RQ2 needs further elaboration since adaptation to the system is directly related to the internal organisation of the product in response to system requirements. Besides, the architecture of the products is very much integrated with only one component satisfying a multitude of functions. Therefore, RQ2 is decomposed into two.

RQ2.1: *What is the internal organisation of the product and how to represent the organisation?*

RQ2.2: *How does the internal organisation of the product affect its interaction with the system?*

Referring to *RQ2* group, better understanding of how the product satisfies its functions is needed. In other words, an architecture description of the product is sought. The product is taken apart in pieces. Since the product is very integrated in nature with only one component (which is the product itself) satisfying a multitude of functions, architecture characterisation of integrated component becomes necessary which is seen to be treated only limitedly in existing literature.

1.1.2 The Industrial context

Within GKN Aerospace, GKN Aerospace Engine Systems develops, manufactures and maintains static aero engine components. GKN Aerospace Engine Systems work together with engine OEM’s who integrate the components into their engines. A number of components for a number of engine architectures (engine types), are designed and manufactured by GKN. Thus, it is necessary to understand and tailor the components to different architectures. By means of the project, GKN develops the ability to evaluate the importance and performance of new engine configurations with their structures in focus. Technology and product development decisions will greatly benefit from the results of such evaluations. Additionally the firm also benefits by an improved understanding about their structures by studying the internal organisation of such structures which presently is not done in a systematic manner.

1.1.3 The Scientific context

An engineering design centric architecture description for integrated components such as those considered in this thesis is, limited in existing literature. This work will focus on how such descriptions can be made so that such products can be represented, modelled and evaluated. One aspect of evaluation is how an integrated component behaves in the system in which it functions. This will lead to creation of method that assesses the impact of product architecture on system level operations. Although such efforts exist already in EU projects (CRESCENDO, 2009, IMPACT-AE, 2013, TOICA, 2013), they are more associated with cooperation among CAD or CAE systems. This work will provide a design theoretical aspect for such multi-disciplinary, multi-level analyses.

1.1.4 Research delimitation

Although the aim is to develop methods and theories of general applicability, the generality is limited at present to aero engine structures context, since the work is done primarily at GKN Aerospace Sweden AB. The studies concern only static structures for commercial aero engines. Although the considered static structures are part of either the compressor or turbine module, the design effects from compressor or turbine modules are also not considered in detail.

2 Frame of Reference

This chapter provides a theoretical framework for the thesis, describing the general definitions of product development, product architecture and means to extract function-means (part 2.2) information of a product. Part 2.3 surveys existing efforts both in industry as well as academia to explore system level effects of component designs.

2.1 Product development

Ulrich and Eppinger (1995) define product development as *the set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product*. Five major activities are defined for product development which are *concept development, system level design, detail design, testing and refinement* and *production ramp up*. According Ullman (2010) there are 4 phases during the life of a product. These are the *product development, production and delivery, use* and *end of life.* For a large project such as the development of a commercial aero engine, in addition to the OEM responsible for the engine, several suppliers will be involved in the development. The role of certain suppliers will be prominent at certain phases of development while at other phases, not so important.

As was stated in the introduction, requirements on products can change throughout the lifecycle of an engine development program. However, the main product interfaces are frozen quite early. Thus physical arrangement of the product or in other words, the architecture of the product is decided early.

2.2 Product architecture

Theoretical discussions and definition of product architecture took steam after the paper by Ulrich (1995) which is later expanded by Ulrich and Eppinger (1995). They define product architecture in terms of functional elements and physical elements. Functional elements are the individual operations and transformations that contribute to the overall performance of a product. For example, for a static aero engine structure, located between the LP and HP compressors of a two-shaft engine, one of the functional elements will be to 'transfer core flow between LP compressor and HP compressor'. Physical elements of a product are the parts, components and sub-assemblies that ultimately implement the product's functions. The physical elements are organised into several major building blocks called 'chunks'. Chunks are formed by the components of the product. Product architecture then, according to Ulrich and Eppinger (1995), is the scheme with which the functional elements are arranged into physical chunks and by which the chunks interact. It is possible to define two types of architectures, modular and integral. In general, when one or a few of the functional elements are satisfied by a single chunk, the architecture is modular. In case of an integrated architecture, multiple chunks act together to satisfy one or a few of the functional elements. An integrated architecture product is therefore a case where a very high degree of 'function sharing' (Ulrich and Seering, 1990) occurs.

In a commercial aero engines context, modular architecture is seen to be applied to an engine as a whole. For instance, the GEnX engine by GE Aviation has two main modules, the fan and the propulsor module (figure 3). The fan module is relatively low maintenance and often stays on the wing of the aircraft while the propulsor module that contains the compressor, combustor and turbine can be detached from the fan module for maintenance. When it comes to individual components such as the structures associated with compressors or turbines, the design is very integral, with only one component satisfying multiple functions. Such components are often manufactured by single piece castings or welding multiple cast or forged pieces together.

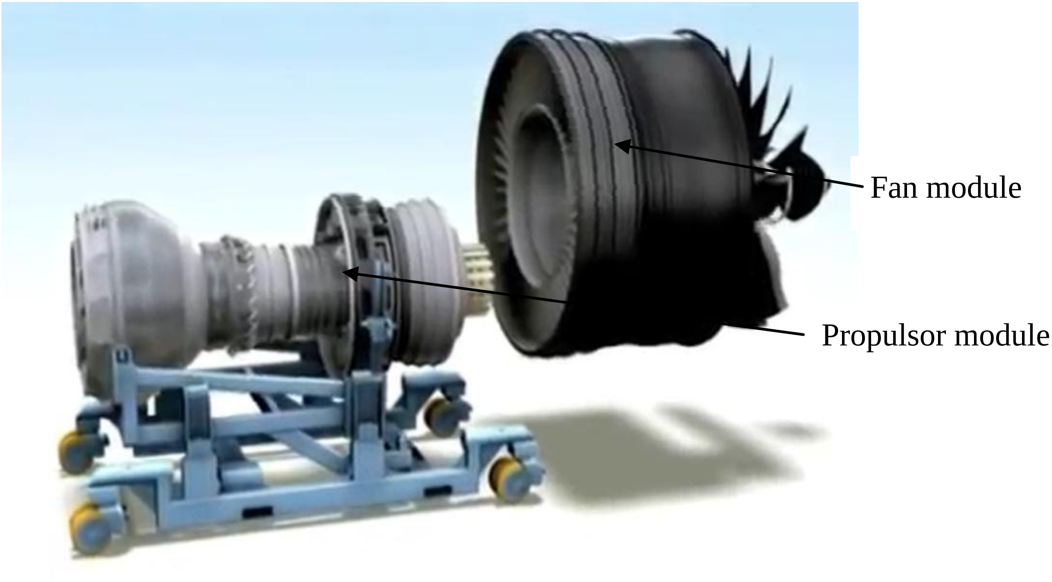

Figure 3 the fan and propulsor module for a GEnX engine (GE Aviation, 2011)

2.2.1 Functional decompositions

The internal organisation of a product is better understood if design decomposition is performed. Kusiak and Larson (1995) define three kinds of decompositions present in mechanical design: product, process and problem decompositions. For product decomposition, structure of the product is decomposed into individual parts. In case of problem decomposition, the requirements are decomposed and for process decomposition, different activities are isolated. Some methods of representation are also discussed in the paper. In this thesis, it is the design problem that is tried to be decomposed.

A review of three functional decomposition methods in engineering was done by van Eck et al. (2008). The *functional basis* approach (Stone and Wood, 1999), the *function-behaviour-state* approach (Umeda et al., 1996) and the *functional reasoning* approach (Chakrabarti and Bligh, 1994). All the methods are suited for documenting an existing design and generating new designs. Using the summary by van Eck et al. (2008), table 1 provides a short description and summary of the decomposition process for each method.

Table 1Functional basis approach, function-behavior-state approach and functional reasoning approach towards functional decomposition as in van Eck et al. (2008)

	Functional Basis approach	**Function Behaviour State approach**	**Functional Reasoning approach**
Short description	Aims to model overall product functions as a set of connected sub-functions. The sub functions are described using a predefined vocabulary.	Reported to be particularly suited for the synthesis phase of the design. Functional descriptions are transformed to structural descriptions of would-be products.	Adopts a prescriptive stand towards designing. Aims to provide *physical descriptions of designs, sufficient for their implementation*.
Decomposition strategy	Functions are modelled as operations on flow, material, energy and signals and using a library of basic flows and basic operations, decomposition is achieved.	Function is expressed as a behaviour that exhibits the function. States are structures in the product. Decomposition is achieved by task decomposition that results in function-state mapping and causal decomposition of task decomposed functions, that results in function-state mapping (which could not be mapped onto function-states in the first pass)	Recursive function-structure mapping incorporating partial function-structure solutions in each successive stages of reasoning in the process.

The function means tree

The functions mean tree (Hansen and Andreasen, 2002) models the function and the means (ways) to satisfy the function. It results in breakdown of a product into multiple F-M levels. For instance, a static engine structure can be represented as an F-M tree as shown in figure 4. The top level function 'transfer core flow' is satisfied by means of the a 'flow path' which in turn has two subsidiary functions 'retain shape' and 'offer least flow resistance' which are satisfied by having a 'rigid structure' and 'streamlined shape' respectively.

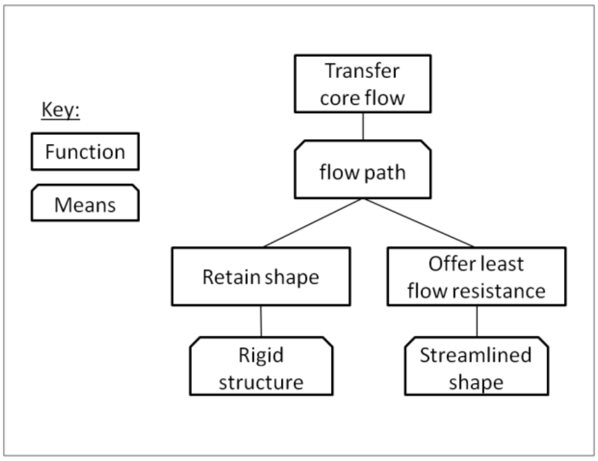

Figure 4 A Functions – Means (F-M tree)

Subtract and operate procedure

The 'subtract and operate' procedure is based on removing one component from a product at time and allowing it to operate, either physically or mentally. The effects of removing the component are noted and from the effects, the function for the removed component is deduced. The component is then put back into the product and a second component is removed and the procedure is repeated until all components are removed and functions ascertained. The procedure is similar to the 'product decomposition' performed by Ullman (2010).

Function analysis system technique (FAST)

The FAST technique (Bytheway, 2007) originated in value analysis where the aim is to maximise the function of a product relative to its cost. For value analysis, a method to analyse a product's functions was needed and this led to the creation of FAST technique. FAST involves asking essentially three questions, *How*, *Why* and *When*. *How* should a function be realised, *why* should a function be realised and what happens *when* a function is realised. The questions are asked serially to a satisfactory level and represented in a diagram. The function is expressed as a combination of an active verb and a measurable noun such as 'provide power'. A simple FAST diagram, applied to an aero engine static structure is shown in figure 5. The vertical lines in the diagram represent the system boundary. Function descriptions inside the vertical lines are applicable only to the structure. Going from left to right, the *how* questions are answered and going from right to left, the *why* questions are answered. For instance, from left to write, transferring core flow is achieved by creating a flow path which in turn is achieved by creating and maintaining a stiff structure and so on. And from right to left, a stiff structure should be created and maintained because it creates a flow path because the flow path needs to transfer core flow. When a stiff structure is to be maintained, it results in ensuring safe operations which is achieved by satisfying safety requirements.

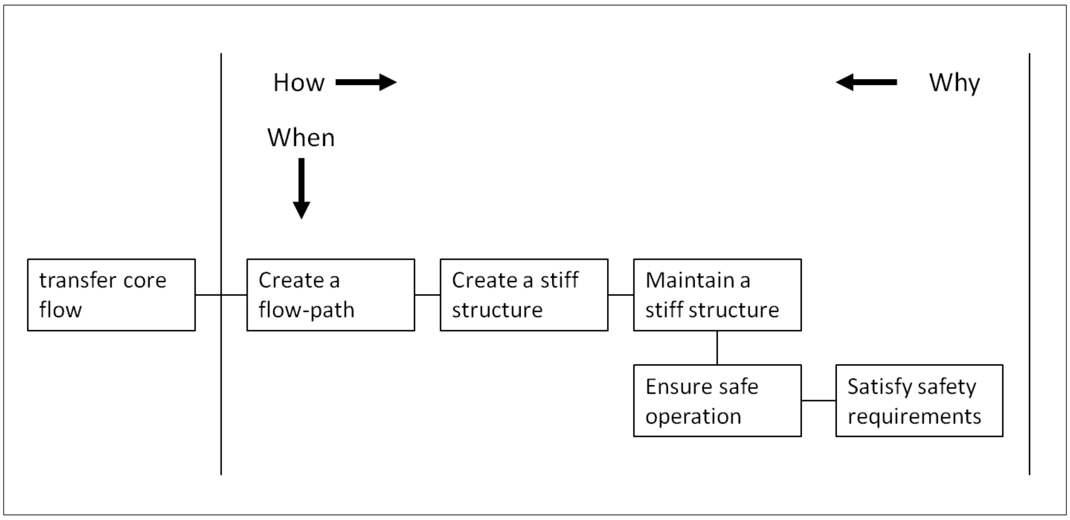

Figure 5 FAST technique applied to a generic aero engine static structure

The configurable component method

The configurable component methodology starts with the creation of an enhanced function-means tree (Andersson et al., 2000, Johannesson and Claesson, 2005) that includes the functional requirements (FR), a design solution (DS) and constraints (C) associated with the design solution. The functional breakdown can be done at multiple levels. No physical form needs to be associated with a DS (DS can also be services) and when a form is associated with a DS, it is said to be satisfied with a component (CO) which is a physical component. A representation of configurable component method is shown in figure 6.

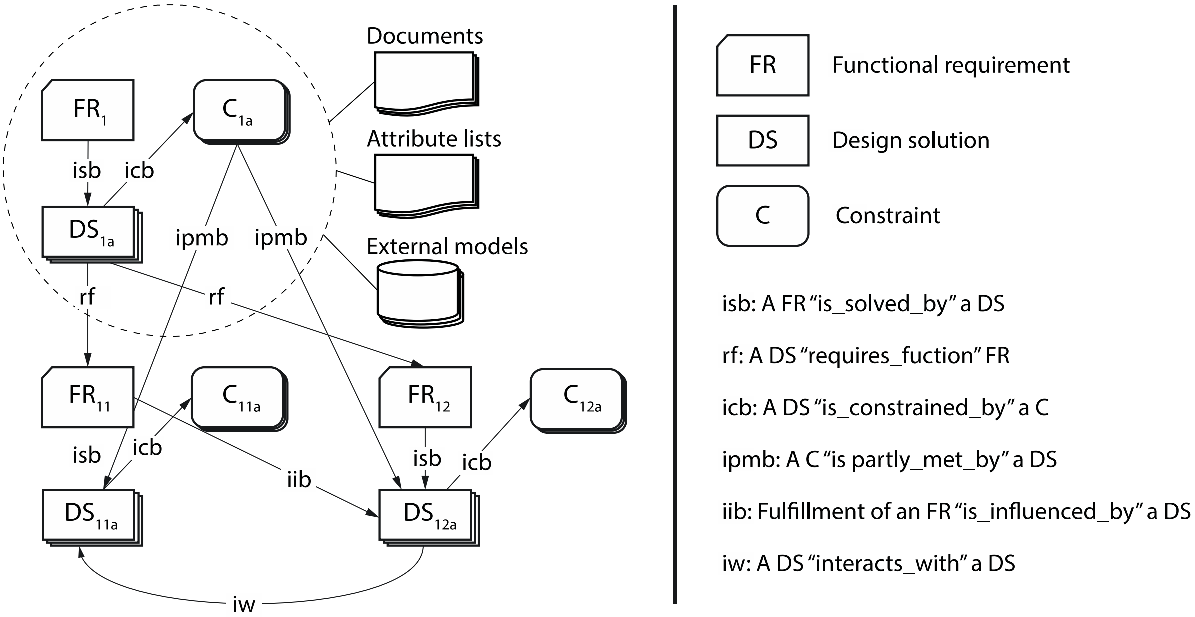

Figure 6 The enhanced function – means tree from (Johannesson and Claesson, 2005)

The relations between the functional requirements, design solutions and constraints at the same level and among different levels are indicated by arrows that are termed with specific names as shown in figure 6. In the simplest sense, when the FRs, DS and C at a certain level are taken together, the resulting object is called a configurable component (CC). Thus, an entire system can be broken down into a number of system objects (CCs). The FRs, DSs and Cs included in a CC can be given parametric values making the CC's configurable. The method is especially useful in creating systematic product platforms and some of the applications are detailed in work by Levandowski (2014) and Michaelis (2013).

Closing remarks

In the work considered in this thesis, an immediately realisable approach was adopted to decompose functions and means to the structures under consideration. This was based on the procedure described by Ullman (2010). From the author's own experience, the easiest way to associate a function to means is through form. In case of integrated architecture structures, this will be regions or areas of the structures that mainly contribute to satisfying the required functions.

2.2.2 Graphs

One of the works on which this thesis is based on uses a graph to describe the functionally decomposed product. A graph G is a finite non empty set of objects called *vertices* together with a (possibly empty) set of unordered pairs of distinct vertices of G called *edges* (Chartrand and Lesniak, 1996). Figure 7(a) shows a graph for which set of vertices is

$$V = \{v1, v2, v3, v4, v5\}$$

and the set of edges is

$$E = \{(v5, v1), (v1, v3)\} = \{e1, e2\}$$

For the purposes of this thesis, one set of vertices will be formed by the set of functions that are required of a class of products and another set of vertices by the sections (regions or features of the product that satisfies functions) of the products. Consider the example of a coffee cup figure 7(b). The functions that the coffee cup is expected to satisfy are a) *carry coffee* b) *be able to be held in hand*. The sections (Raja and Isaksson, 2015) that the cup has are a) *cylindrical region* where coffee is held and b) the *handle*.

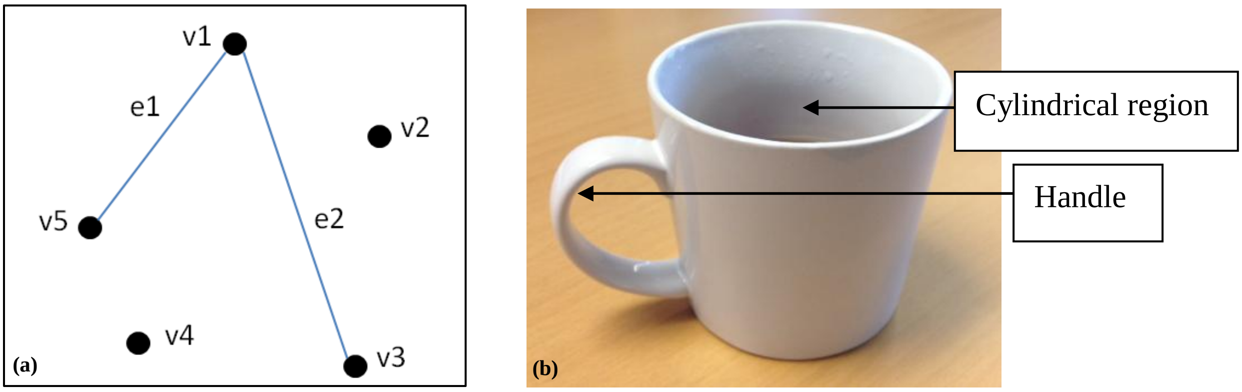

Figure 7 a) example of a graph with 5 vertices and 2 edges b) sections in a coffee cup

Extending this logic, each structure that belong to a class can then be represented as a graph where the vertices are the functions and sections of the structures and the edges are the relationships between them; that is which sections contribute to satisfying a function.

2.3 Exploring system level effects

Performing a computer based design of experiments (DoE) is a common method in the industry to explore system level effects due to local changes. The general procedure is as follows. A parametric CAD model for the system under consideration is prepared which might have several variables parameterised. Next, a DoE scheme suited for screening[2] of the variables is used to generate a number of CAD models for the system. The CAD models are evaluated using CAE (computer aided engineering) packages appropriate for the physics of the problem. The results from the CAE evaluations are the system responses which are used to find out which variables affect the system the most. Depending on the problem, further actions may be performed such as creating another DoE with only the variables that are present after screening, so that a response surface for the system response in terms of the variables after screening is obtained. This response may be used in an optimisation problem for the variable.

When the concerned system is very large, the parametric CAD model for the system will have

[2] With a screening DoE scheme, the 'main effects' for the set of variables under consideration is evaluated. Main effects are an indication of the sensitivity of system response to changes in the variable under consideration.

a large number of variables and it becomes difficult to screen which variables are important. Therefore it becomes necessary to employ system decomposition methods so that the problem under consideration is manageable. Eppinger (1997) proposes a planning method based on design structure matrices (DSMs)[3] for evaluating system interaction after decomposition has been made.

The area of knowledge based engineering (KBE) and knowledge based systems (KBS) is largely utilised to model dependencies and perform integrated design studies. Dixon (1995) provides a definition of a knowledge based system and presents early research efforts at creating such a system for a simple product. Larger products and systems will require decomposition of the problem. Many of the works done in KBE and KBS also focus on optimisation. Particular focus is often directed to multi-level, multi-objective and multi-disciplinary optimisation techniques. Several methods to decompose an engineering system optimisation problem as a number of multi-disciplinary problems exist. Dépincé et al. (2007) provide an overview of such techniques. Van Tooren et al. (2005) describe methods to coordinate the design efforts for a freighter aircraft using Knowledge Based Engineering (KBE) principles. The work also describes a software tool that functions as a coordinator for design of the component making use of multi-disciplinary optimisation and applies the tool to the actual design of a composite aircraft wing component. Jarrett et al. (2007) propose an approach to the integrated multidisciplinary design of turbo machinery. This work also relies on coordinating efforts from different design teams. To facilitate coordination, they also propose a software tool. Rather than optimisation, minimising the differences between an ideal design and currently achievable design is the focus of the work. Example of application of the methodology is shown on the design of a core compressor.

Common to both Van Tooren et al. (2005) and Jarrett et al. (2007) are the creation of a tool to coordinate different activities performed within design teams. This is done by coupling different design inputs and outputs with respective systems at appropriate hierarchical levels.

Moving focus to published examples from the industry, Reinman et al. (2012) describe ‘design for variation (DFV)’ that uses various statistical techniques to improve the design of components at Pratt Whitney in addition to performing multidisciplinary analyses. Improving different design requirements on a turbine airfoil is demonstrated in the paper. Sandberg et al. (2011) describe a study performed on rotating machinery that uses KBE methods.

Concluding remarks

Detailed and extensive information is necessary to evaluate component-system interactions in an integrated machine such as an aircraft engine. This information is often the result of expensive physical testing which are conducted during later phases of the development project. At the early design phases, such test information is impractical but at the same time, information about possible system-component interactions are needed at this phase so that alternative product architectures can be introduced and evaluated for its effects.

[3] DSMs are matrices that represent the interaction between different components in a product. DSMs are used for representing the product architecture.

Computational methods are ideal for such early design evaluations which are fast and cost effective compared to physical testing. Continued work from this thesis will concentrate on evaluating the component-system interaction effects using optimisation and coordination frameworks such as analytical target cascading or ATC (Kim et al., 2003) among others.

3 Research Approach

According to Blessing and Chakrabarti (2009), the research question determines the research approach. This work is a mix of quantitative as well as qualitative research. An overall framework that is suited to either quantitative or qualitative research will not applicable in this work. All aspects of the work concerns engineering product development and a framework that is close to product development needs to be adopted as the research approach. Design Research Methodology (DRM) proposed by Blessing and Chakrabarti as well as the Spiral of Applied Research (SAR) (Eckert et al., 2003) are close to engineering product development and these approaches will be discussed below. Additionally, the aim of DRM is to produce better design methods so that better products are created. In that sense, the work in this thesis is also focused on producing better methods so that better products are created and thus, this research can be termed a design research.

3.1 Frameworks for design research

Citing a lack of methodology in design research, Blessing and Chakrabarti introduces DRM. DRM defines 4 phases for the research project which are research clarification, descriptive study I, prescriptive study and descriptive study II. These phases, the main outcomes from each phase and the basic means to achieve these outcomes are shown in figure 8.

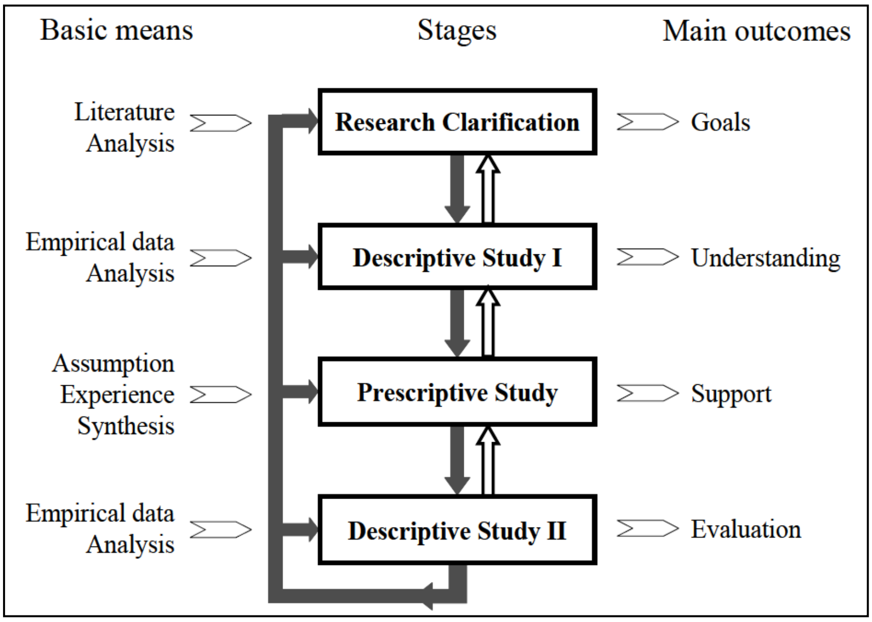

Figure 8 DRM phases from Blessing and Chakrabarti (2009)

During the research clarification phase, goals of the research project are formulated. The present and desired situation are described and criteria are defined which will indicate how much the present situation has moved towards desired situation.

During *descriptive study I*, increased understanding of the present situation is created through empirical studies which may involve literature review as well. This phase identifies a number of factors that influence the existing situation.

During *prescriptive study*, the increased understanding of the existing situation is used to improve the description of the desired situation. By varying one or several of the factors identified in the descriptive study, a support or a preliminary suggestion to move towards the desired situation is suggested, making sure that the support is implemented correctly.

Descriptive study II focuses on studying the impact of the proposed support during the *prescriptive study*. Empirical studies are used to calculate the criteria defined in *research clarification* phase to assess whether the support has improved the present situation.

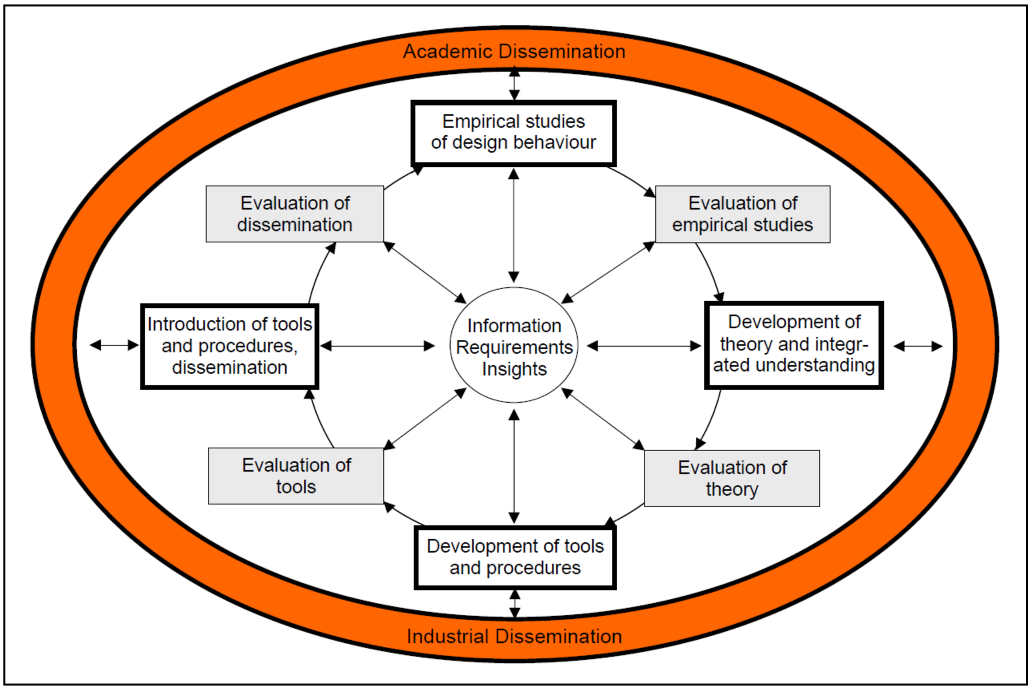

Figure 9 The spiral of applied research, from Eckert et al. (2003)

Eckert et al. (2003) propose a *spiral of applied research* which includes 4 activities from which a research project may get started. These are *empirical studies of design behaviour*, *development of theory and integrated understanding*, *development of tools and procedures* and *introduction of tools and procedures*. In figure 9, the activities are noted inside white boxes. The SAR is claimed to be suited for larger projects where multiple people take part in the research activity.

Thus, it can be argued that DRM is appropriate for a PhD project where the only resource is often the PhD student while SAR is applicable for larger research projects. In this work, it was stated before that a parallel PhD project is running at the applied mechanics division of Chalmers University of Technology. Such combined efforts can be placed under the SAR framework.

3.2 Research approach in this project

Since the project is carried out in close cooperation with the industry (the author has been located primarily at the case company rather than at the university), with reference to the DRM approach, much of the information necessary for research clarification is available. The research questions need delineation but there is a pre-existing goal, defined at a project level.

The work that is so far done in this project is in the form of academic papers which can be arranged as in table 2.

Table 2 PhD project in a DRM framework

Paper A	Generic Functional Decomposition of an Integrated Jet Engine Mechanical Sub System Using A Configurable Component Approach			
Paper B	Exploring Influence of Static Engine Component Design Variables on System Level Performance			
Paper C	A study on integrated product architecture characterization			
DRM stage	**RC (Clarification)**	**DS I (Understanding)**	**PS (Support)**	**DS II (Evaluation)**
Paper A	✓		✓	✓
Paper B		✓	✓	
Paper C	✓	✓	✓	✓

Eckert et al. (2003) suggest the applicability of SAR approach to larger projects and projects that are multidisciplinary in nature. It was indicated before that a parallel PhD program is investigating what kind of changes are likely at the engine (system) level operations. In view of the larger context of the project that this licentiate work is part of, the papers will span 270^0 of the spiral of applied research (with contributions from the parallel PhD project as well though not included), shown in table 3.

Table 3 Stages of project, located on SAR

Empirical Studies		**Theory development and understanding**		**Tools and procedure development**		**Dissemination of developed tools and procedures**	
Study	Evaluation	Study	Evaluation	Study	Evaluation	Study	Evaluation
			A	A	A	A	A
				C	C	C	C
				B	B		

Note that table 2 and table 3 do not show how deep the contributions of the papers are. They only serve to show the span of the works included in the licentiate thesis.

3.3 Research Quality

The quality of research is often expressed in its reliability and validity. In this thesis, reliability implies the repeatability of methods so that the same results are obtained each time using the methods. Validity implies how close the results are to the ‘true’ results. Depending on the research methods, different terms such as validity and verification are seen to be used to express results quality. For instance, in qualitative research, the term verification expresses the same ideas of validity for design research. Pedersen et al. (2000) propose a research validation approach called the validity square. The validity square was proposed due to the multi-disciplinary (quantitative and qualitative) nature of design research. The validation square checks both the qualitative and quantitative aspects of the research by looking at the theoretical and empirical acceptability work. The validation square adapted from (Pedersen et al., 2000) is shown in figure 10.

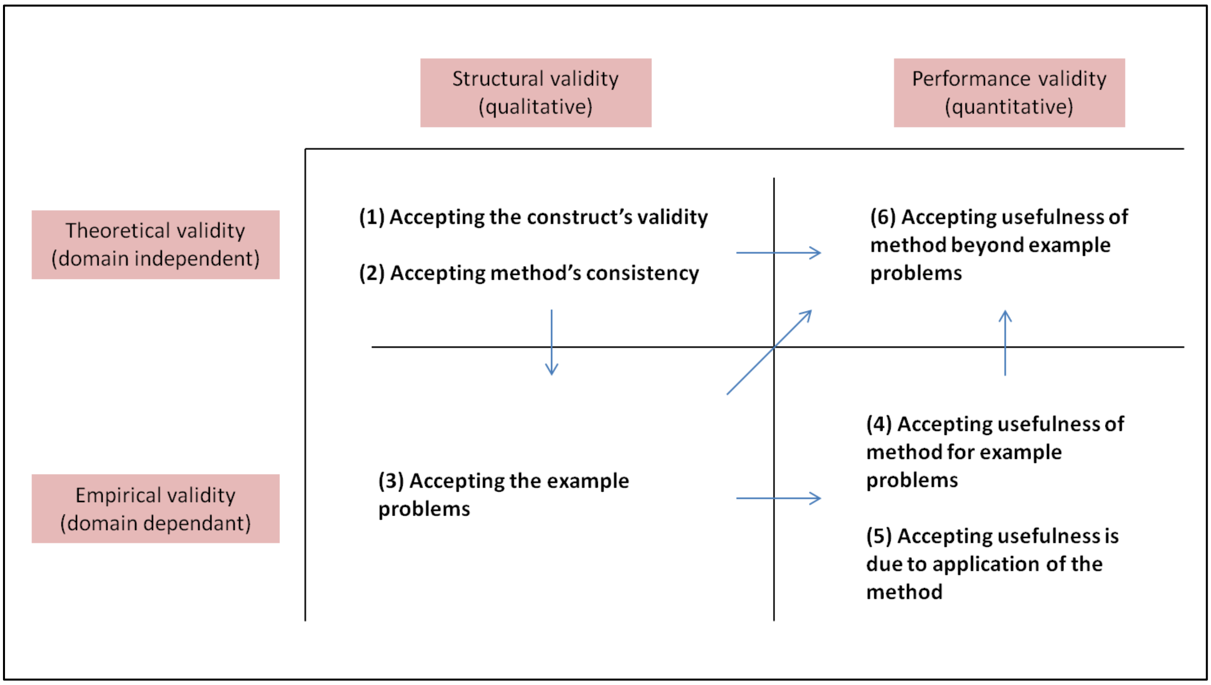

Figure 10 The Validation square adapted from Pedersen et al. (2000)

When each acceptance checks are performed and found to be true, the research work's validity is proven. Each acceptance checks are described briefly below

(1) Accepting the construct's validity: During this check, the logical consistency of the proposed design method is evaluated. If the method is composed of a number of constructs, the individual logical consistency of each method should be established.

(2) Accepting the method's consistency: After establishing construct validity, internal consistency of the entire proposed method in its entirety is established.

(3) Accepting the Example problems: Once the consistencies for the individual constructs and overall methods are established, the suitability of the example problems used to validate the method is ascertained.

(4) Accepting usefulness of the method for example problems: The design method is applied to the example problems considered and the usefulness of the method is established. For instance, in an industrial context, this can be done by noting how much the time or cost is reduced due to the proposed method.

(5) Accepting that the usefulness is due to the application of the method: At this step, it is to be proven that the usefulness exhibited in the example problems is really due to the application of the method. The proposed design method can be compared with existing practices or another method to prove the significance of using just the proposed method.

(6) Accepting usefulness beyond example problems: If steps (1) through (5) are accepted, then it can be stated by induction, that the method is applicable to problems having precisely the same characteristics of the example problems.

Thus, the validity of the design method needs to be examined staring at the (1), (2) squares and proceeding to the other squares as applicable, as the arrows show in figure 10. Part 5.2.3 of this thesis details the application of the validity square to the appended research papers.

4 Summary of the appended papers

Works related to all papers were performed in an industrial context, onsite, since the PhD programme is industrial. The case company is GKN Aerospace Sweden AB who is the author's employer. Three papers are appended here. The first, paper-2 concerns creation of a procedure to extract functions and means from an integrated architecture product and storing the extracted information as configurable components (refer part 2.2.1). Second paper, paper-B, is a work about performing multi-disciplinary analyses so that a measure of strength of coupling between two systems (top and bottom level) is obtained. The third paper, paper-C, borrows a concept from paper-A, and tries to describe the architecture for integrated products. Following is the summaries of the papers. Full papers are available in (Appendix A, appendix B and appendix C). Key results and findings related to the papers appended are given in part 4.4.

4.1 Summary of Paper – A

Generic Functional Decomposition of an Integrated Jet Engine Mechanical Sub System Using A Configurable Component Approach

This paper discusses extraction of functions and means from an integrated aero-engine component by suggesting a procedure for the extraction. The work also details how the decomposed functions and means are saved using a configurable component (CC) framework so that later reuse of the design knowledge is possible. Therefore the paper requires understanding of the CC concept which is detailed in part 2.2.1 (or in the full paper appended in appendix A).

The procedure to extract functions and means is based on a description for functional decomposition by Ullman (2010) that involves taking apart parts of a product and noting each part's function. Listed below is the procedure.

1. Prepare an exhaustive list of functions that the integrated component is required to satisfy
2. Separate the component into identifiable sections
3. Identify constraints associated with each section
4. Create a table in which each identified product section is assigned functions that it satisfies and associated constraints
5. Create an E F-M tree for each section connecting functional requirement, design solutions and constraints
6. Prepare configurable components from the E F-M tree table

When the steps just mentioned are followed on an integrated component shown in figure 11, a table with the functions, means and constraints results which is given in table 4.

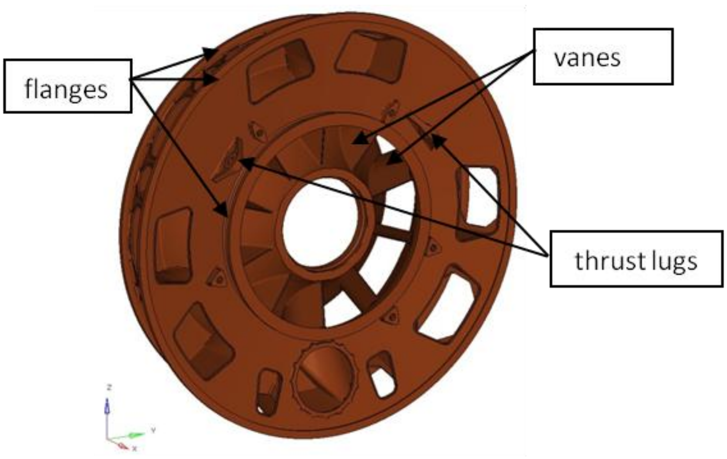

Figure 11 Cold structure designed for the VITAL program (Transport - Research & Innovation European Commission, 2012). Flanges, vanes and thrust lugs marked are various ‘sections’ of the structure.

Table 4 Functions, solutions and constraints

No	Sections (Design Solutions)	Functions that the sections satisfy (Functional Requirements)	Constraints
1	Thrust lugs	transfer thrust loads to aircraft	Length of thrust lug arm diameter of thrust lug thickness of thrust lug angle of inclination of thrust lug distance between the arms of the thrust lug
2	Flanges	act as component interfaces	Inner diameter Outer diameter flange thickness
3	Vanes	connect flow annulus walls transfer rotor loads to engine outer frame induce changes in flow properties	vane thickness vane forming methods (cast/sheet metal) vane height vane length (actual chord, axial chord)

Referring to the second row of table 4, the structure has a number of sections that satisfies the function ‘act as component interfaces’. It can then be assumed that the same CC is instantiated at each section so that the function is satisfied. This is shown in figure 12.

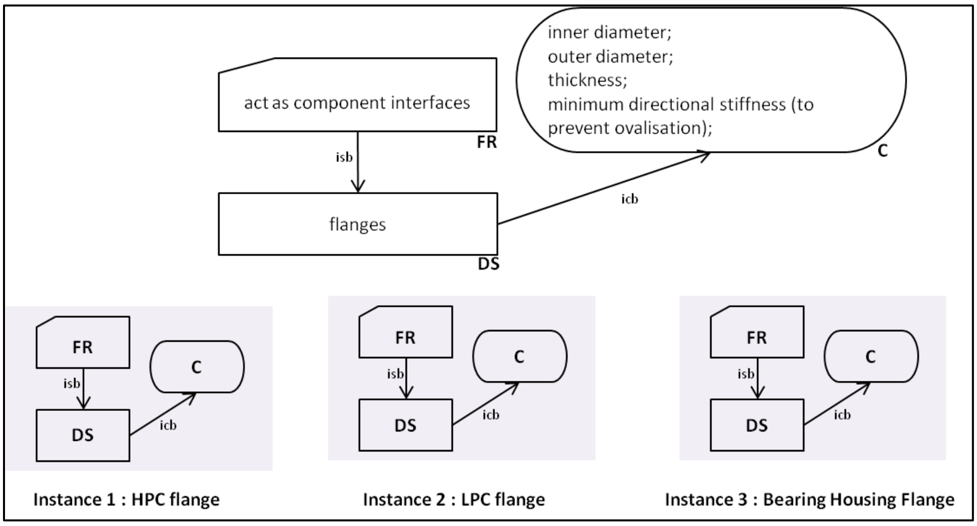

Figure 12CC for flange and 3 separate instances of the CC's

The third row in table 4 has multiple functions that are satisfied by one section. In order to conform to the cardinality (one to one FR-DS relations) of the CC method, generic solution names are used for the CC's concerned and the all CC's are realized in one component CO. This is show in figure 13

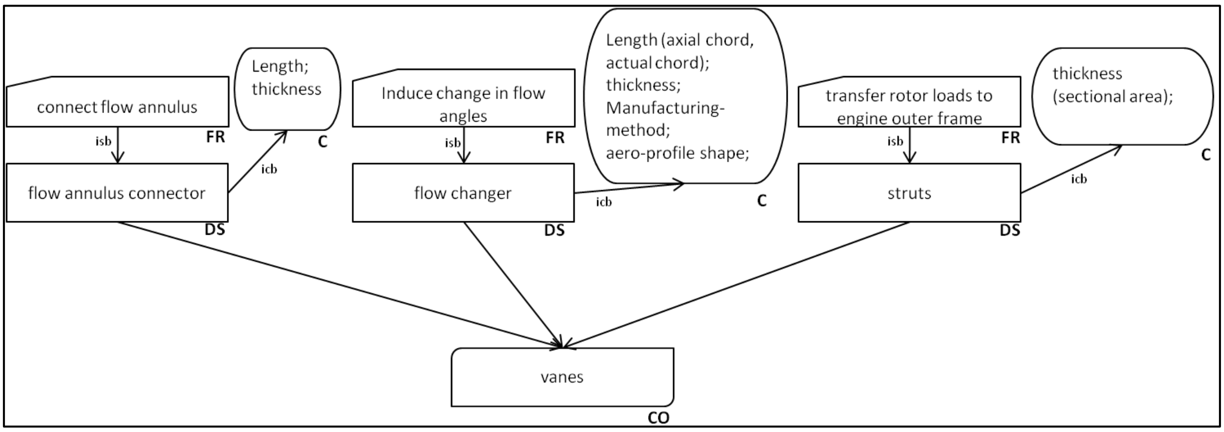

Figure 13 CC for Vane displaying three CC's and the Vane CO.

The markings, 'isb' and 'icb' in figure 13 denote 'is solved by' and 'is constrained by' relations in CC terminology. More information is available in the appended paper.

A CC can be made for the first row in table 4 as well though not shown in this summary.

There are two applications for the stored information in this manner. One is the documentation for the design. Once the E F-M tree is made, it is possible to identify the contribution of different sections towards satisfying the functional requirements. Another application is generation of new designs. Referring to the figure 13, the component (CO) vane realizes 3 CC's. If the vane is made entirely from sheet metal, the structure may not be able to carry loads towards engine outer frame effectively. In this case, the CC for load transfer might need to be realized separately than other CCs. Another CO, struts, can satisfy the load transfer function. The generation of new solutions is shown in figure 14.

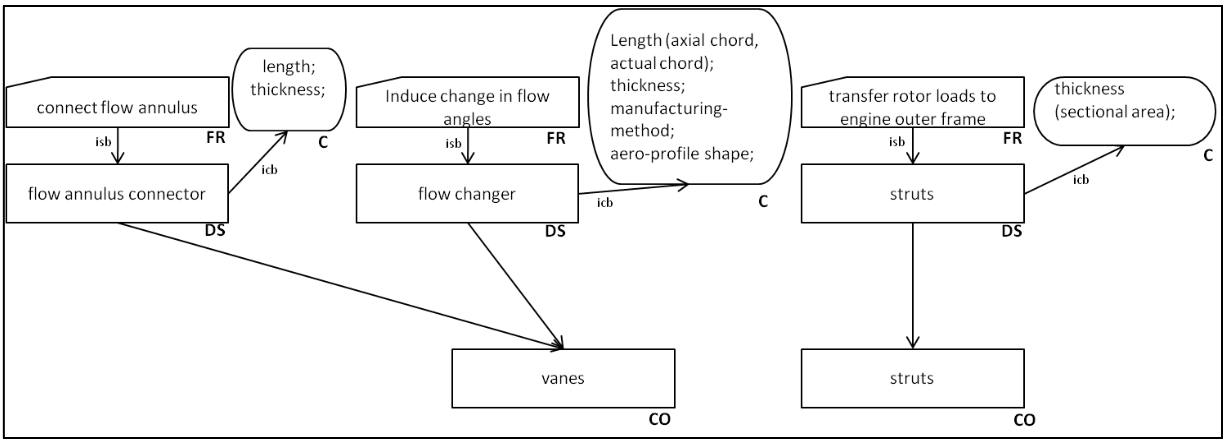

Figure 14 separation of function from a section and formation of new design

The functional decomposition along with storage of the decomposed information in CC's is a useful way of documenting design knowledge and generating new design which can be used in companies like GKN, that design and manufacture integrated products.

4.2 Summary of Paper – B

Exploring Influence of Static Engine Component Design Variables on System Level Performance

This paper discusses a preliminary effort to couple two disciplines related to the design of aero engines. The two disciplines considered are the engine performance predictions (calculations generally performed at the OEM) and detail design efforts (performed at the component supplier, GKN). Engine or system level calculations provide boundary conditions relevant to the design of the component. The design activities for the components occur in a sequential fashion; component design activities continue after receiving system (engine) inputs. If information about component design's influence on system operation is available, components could be better designed and be made more robust to system level changes. This shows the importance of an integrated system and component design.

The component considered in the paper is a turbine rear structure (TRS) often termed a 'hot structure'. The structure is situated at the aft of the engine just after the turbine last stage. Two main functions of the structure are (1) to de-swirl the flow and (2) attach itself to the engine frame among many others. While designing the TRS, important measures of its performance are the pressure drop across the component and the weight. Too high pressure drop or too high weight of the component both causes reduction in engine performance. In order to generate a preliminary measure of the effect of TRS design on the engine level, a number of calculations performed on an aerodynamically well designed[4] TRS were used to find out a range of pressure drops across all designs. Variation in pressure drop is shown in figure 15.

[4] Aerodynamically well designed implies that the TRS is designed such that the out flow from the last turbine stage matches the inflow geometry for the TRS

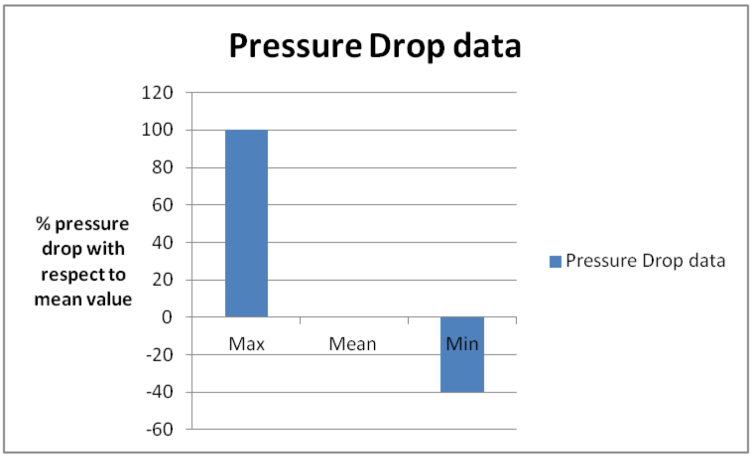

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Figure 15 Maximum and minimum % variation in core flow pressure drop corresponding to TRS design variations

The maximum and minimum pressure was used to calculate the change in efficiency for the LPT turbine which in turns results in a variation in the specific fuel consumption of the engine. The coupling is shown in figure 16.

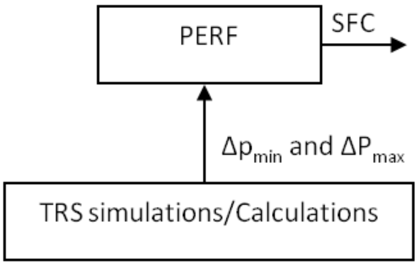

Figure 16 Simulation of system dependency

In a similar fashion, pressure drop for an aerodynamically poorly designed[5] TRS was calculated and the corresponding variation in SFC was found out. The variation in pressure drop that corresponds to the aerodynamically well designed TRS produced an SFC variation of about 0.06%. While using the poorly designed TRS, the variation in pressure drop is 7 times the most minimum value of pressure drop for the optimised TRS. This in turn causes the SFC to vary by about 0.9% larger than that found for the aerodynamically optimised TRS. table 5 shows the summary of results.

[5] Aerodynamically poorly designed implies that the TRS inflow geometry does not match the outflow characteristics from the last turbine stage

Table 5 Performance of Aerodynamically non-optimised TRS with respect to an aerodynamically optimised TRS

	Pressure drop	SFC
non optimised TRS with respect to aerodynamically optimised TRS data	7 times more	0.9% more

Even a minute reduction in SFC is significant for an airliner's fuel costs. Thus, it is evident that system level effects are important information to the suppliers and there is merit in an integrated design of the component with the overall system so that performance is optimised. It also proposed that an optimisation framework, called analytical target cascading or ATC (Kim et al., 2003) be used for the coordination in future calculations.

4.3 Summary of Paper – C

Describing and evaluating functionally integrated and manufacturing constrained products

This paper is about representing the product architecture (physical organisations of parts in a component to satisfy the functions) for an integrated product including alternative manufacturing options. For integrated products, conventional architecture representations such as DSMs (Design Structure Matrices) or node link diagrams are insufficient in indicating how the product satisfies the functions required of it since the matrices have only one element in it. In order to solve the representation problem, it was proposed that each manufactured segment (Ms) of the product (such as a cast segment) be associated with a generalised function and a generalised section. Generic functions (GFs) are the collection of all functions that a class of products are typically required to satisfy. Generic sections (GSs) are the collection of all regions present in different products that contribute to satisfying the functions. Since the same manufactured segment of the product is associated with generalised functions and generalised sections, a GF-GS mapping can be represented in a graph, where GFs and GSs form the nodes and relations between GSs and GFs form the edges for the graph.

Let GF be the set of functions, M be the set of manufactured segments and GS be the set of sections. Let G1 be the graph that connects functions to manufactured segments and G2 be the graph that connects manufactured segments to sections. Graphs G1 and G2 are essentially functions f1 and f2 that associate functions (the functions of the component) to manufactured segments and manufactured segments to sections. The composition (Goldrei, 1996) of f1 and f2 can be written as,

$$\mathrm{f1} : \mathrm{GF} \rightarrow \mathrm{M}$$

$$\mathrm{f2} : \mathrm{M} \rightarrow \mathrm{GS}$$

$$\mathrm{f2 \ o \ f1} : \mathrm{GF} \rightarrow \mathrm{GS}$$

To illustrate the generic function and generic section association through the manufactured segments, the functions and sections for a pump casing was considered as depicted in figure 17 (a) and (b). In the paper, three different options to manufacture the pump is explained though in this summary, only one such option is shown, which is welding 4 cast segments to produce the pump casing, show in figure 17 (c).

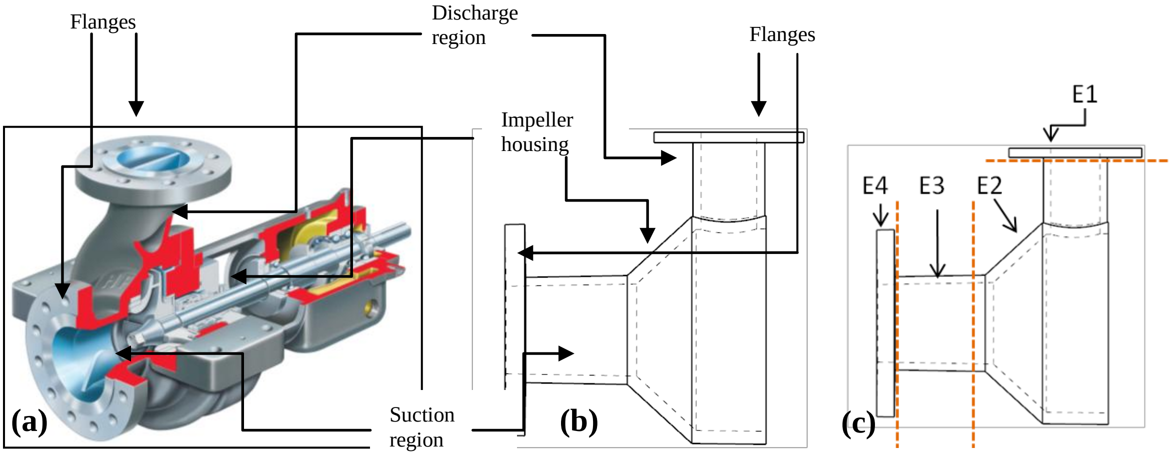

Figure 17 (a) Sections for centrifugal pump casing (Flowserve Inc) and (b) simplified cross sectional view. c) 4 manufactured segments: E1, E2, E3 and E4 as castings

The mappings from generic functions (GFs) to generic sections (GSs) are then achieved as,

$$\mathrm{GF} \rightarrow \mathrm{GS} : \ \mathrm{GF} \rightarrow \mathrm{M} \circ \mathrm{M} \rightarrow \mathrm{GF} \ \text{ where}$$

$$\mathrm{GF} = \{\text{intercomponent\_attachements}, \text{house\_impeller}, \text{allow\_discharge}, \text{allow\_suction}\}$$

$$\mathrm{M} = \{\mathrm{E1}, \mathrm{E2}, \mathrm{E3}, \mathrm{E4}\}$$

$$\mathrm{GS} = \{\text{suction region}, \text{discharge region}, \text{impeller housing}, \text{flanges}\}$$

The graph for the 4 segment pump can be created as shown in figure 18.

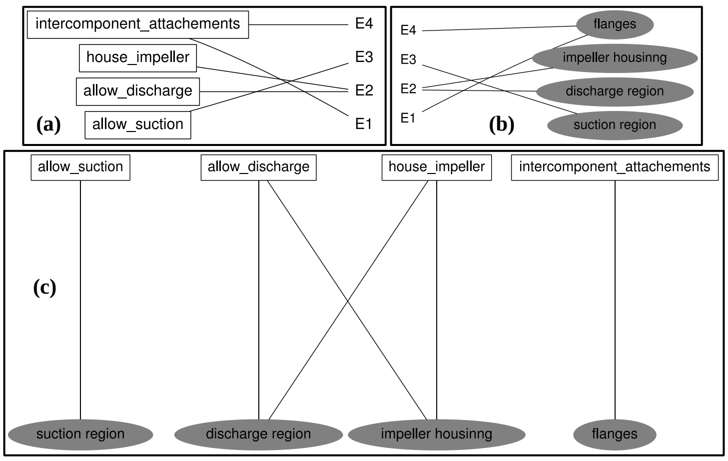

Figure 18 generic functions (GF) to manufactured segments (M) mapping (GF-M) for design-2 b) manufactured segments (M) to generic sections (GS) mapping (M-GS) for design-2 c) generic sections (GS) to generic functions (GF) mapping (GF-GS) for design-2

In addition to the approach that associates manufactured segments to GFs and GSs, an enhanced function-means (EF-M) (also see part 2.2.1) tree for the components was created so that already existing design knowledge can be included in the architecture representation. Graphs could then be generated from the axiomatic design matrix (iib-matrix) that the EF-M tree generates which is similar to the initially created graph but with more refined functions to sections to relationships in it. Figure 19 shows the enhanced function-means tree for the 4 segment pump casing with the graph created from an axiomatic design matrix.

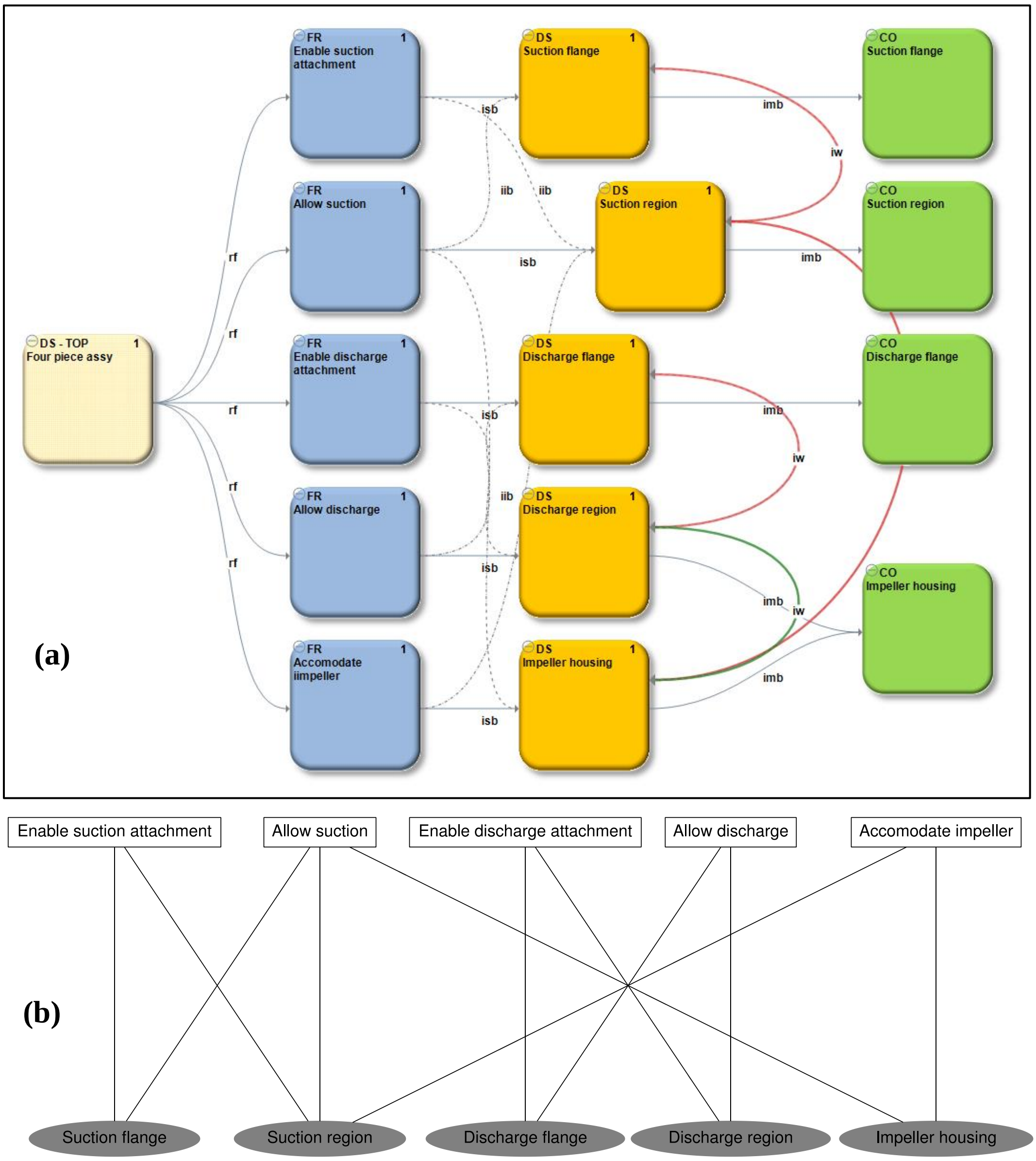

Figure 19 (a) EF-M tree for the 4 piece pump casing design. The 4 pieces are welded together to produce the casing (b) Graph created from the iib matrix for the 4-piece pump casing design.

This approach of dividing the structure into sections is essentially assigning modularity for an integrated component. Holtta-Otto and de Weck (2007) demonstrate fully integrated products, bus modular products and fully modular products using singular value decomposition (SVD)[6] of the respective design structure matrices. When the singular values are sorted in descending order, integrated architecture products show a quick decay pattern while fully modular product shows a more gradual decay pattern. The decay pattern for the adjacency matrix for a revised initial graph (with 5 functions and 5 sections instead of 4 functions and 4 sections) was compared to the decay pattern for the adjacency matrix of the graph from the iib matrix to see how the modularity arising out of the product descriptions (initial as well EF-M based) compares. The SVD decomposition patterns for the 4 segment pump casing are shown in figure 20 (for other designs, please see the full paper in appendix C). For the 4-segment manufacturing option, the SVD decay pattern is more gradual, similar to the decay pattern for graphs for modular designs. The SVD decay pattern for a 4-segment casting option, using EF-M tree iib matrices show a much gradual pattern when compared to the pattern generated from the initial graph description. This is a result of manually removing a number of non-influencing sections to function relations. Thus, despite the initial graph description being a quick method, it results in grouping complexities in the product. This can be rectified if looked at by a designer using the EF-M tree, a fact demonstrated by the difference in decay patterns for the initial graph and EF-M generated graph, shown in figure 20.

The most important nodes in a graph are often determined by the centrality of the graph. *Degree centrality* notes the number of incident edges on to a node. The node with the greatest number of incident edges is the most central node in the graph. Since the graphs considered here are undirected (edges do not indicate directions) and bipartite (meaning that relations exist only from the set of general functions, GF, to the set of general sections, GS and no relations exist within the GF and GS set), there is no hierarchy that can be observed in the graph. A function is satisfied by one or several sections and the sections in turn do not give rise to sub functions or sub sections. The most important section can be identified by looking at the section that has the highest degree centrality. This just means that the section with the highest degree centrality contributes to satisfying a number of functions. In the initial graph for 4-segment pump (figure 20 (b)), sections 'discharge region' and 'impeller housing' both have a degree of 2 (2 incident edges). In the EF-M tree generated graph, where more relationships among sections were manually identified, the section with the highest degree is 'suction region' which was un-identified in the initial graph.

To ascertain the importance of GF – GS relations, a centrality measure for the edges, the *edge betweenness centrality*, can be used. The *edge betweenness centrality*[7] for an edge is defined as the ratio of the number of shortest path passages (between all pairs of nodes in the graph) through the concerned edge to the number of total number of shortest paths (between all pairs of nodes in the graph) in the graph. With respected to the GF – GS relationships, a particular GF – GS edge with a high *edge betweenness centrality* indicates that this edge (relationship)

[6] The singular value decomposition (SVD) for any matrix M can be expressed as $\mathrm{M} = \mathrm{U}\,\Sigma\,\mathrm{V}^{\mathrm{T}}$ where U and V are orthogonal matrices and Σ is a diagonal matrix containing the Eigen values of M. SVD is often used for finding the structure of matrices and compressing information contained in matrices.

[7] For a graph G, the betweenness centrality of an edge, e, is defined as $\mathrm{EB(e)} = \sum_{\mathrm{v_i}} \sum_{\mathrm{v_j}} \frac{\sigma_{\mathrm{v_i v_j}}(\mathrm{e})}{\sigma_{\mathrm{v_i v_j}}}$ where $\sigma_{\mathrm{v_i v_j}}$ is the number of shortest paths between edges $\mathrm{v_i}$ and $\mathrm{v_j}$, and $\sigma_{\mathrm{v_i v_j}}(\mathrm{e})$ is the number of shortest path that passes thorough edge e.

needs to be traversed a number of times when tracing any function to a section in the graph which indicates that the edge (relationship) is an important one in terms of the integrity of the structure. When a particular function is satisfied by sections other than those intended for satisfying the function (cross relationships), important cross relationships can be identified by looking at the cross edge with high *edge betweenness centrality*. For the 4 segment pump casing shown in figure 20 (b) and figure 20 (c) the cross edges in each graph with the highest degree centrality are highlighted. *Betweenness centrality* for the initial graph predicts high importance for only 1 relationship which is, *allow_discharge – impeller housing*. However, with the EF-M tree generated graph, where relationships have been manually modified, 3 relationships (*allow discharge – suction flange*, *allow suction – impeller housing*, and *enable discharge attachment – discharge region*) with high *betweenness centrality* are identified.

Thus, the GF to GS associations, performed as in the initial graph creation might not identify important GF-GS relations which are manually identified while creating the EF-M tree. The initial GF to GS relationships are also revised during the creation of the EF-M tree. A combined look at the all the cross relations predicted will give the designer information about which sections of the design should be paid attention to while deciding on a manufacturing split. The methods considered can be used as a sequence of measures to generate and evaluate information about integrated products. An initial function section association combined with the creation of detailed EF-M trees thus help designers realise the implications of different manufacturing options on the functional realisation at quite an early stage. Therefore product architecture evaluation based on manufacturability considerations is facilitated. The methods may result in appropriate resource allocations and planning in both the design and manufacturing departments once decision regarding a certain manufacturing option is made.

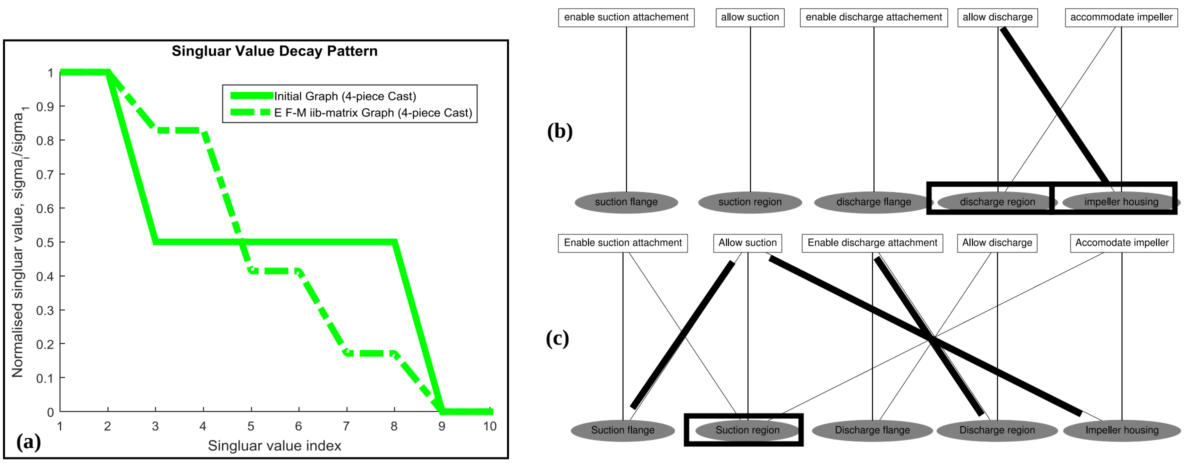

Figure 20 **(a)** SVD decay pattern for the graph descriptions for 4-piece cast (manufacturing option-2) pump casing, using initial graph generation approach and iib matrix **(b)** Initial graph for fully cast pump casing option with highest edge-betweenness centrality cross relationships highlighted. Sections with highest degree centrality are also highlighted **(c)** graph from EF-M tree created for fully cast option with highest edge-betweenness centrality cross relationships highlighted. Section with highest degree centrality are also highlighted

In addition to the pump casing example as just described, the same approach was applied to a vane section of an aero engine component the details of which can be found in appendix C where the full paper is attached.

4.4 Key results and findings from the papers

Related to product improvement at the firm these are the key results and findings.

- A way to decompose functional requirements and design solutions (sections) in an integrated architecture component is proposed. Using the procedure, an F-M tree (strictly speaking an enhanced F-M tree) is created for an integrated architecture component which is otherwise difficult.
- The usage of configurable component method towards documenting and re-using the F-M information is demonstrated.
- The work is similar to assigning a virtual modularity for integrated architecture structures.
- Product architecture descriptions can be created by associating the functional requirements and sections through manufactured segments such that the information is represented in a graph.
- The virtual modularity captured in the graph enables architecture evaluations on the component.
- The architecture descriptions created allow designers to realise the implications of a certain manufacturing option
- The architecture descriptions may result in appropriate resource allocations and planning in both the design and manufacturing departments once decision regarding a certain manufacturing option (split) is made.

Key results related to the products' behaviour at system level end are:

- A framework is generated to predict the effect of supplier's component on system level. This is done by means of a coupling study between two disciplines.
- By means of the coupling study, a quantitative measure is obtained for the strength of coupling between the disciplines. The measure also indicates how strongly the supplier's and the customer's design teams should cooperate.

5 Discussion

5.1 Answering the research questions

5.1.1 RQ1

How does the product behave in the system?

There are two aspects of finding the behaviour of the product in the system. One is finding a measure, a value that indicates the performance of the product in the system. This can be achieved by conducting coupled simulations for key measures that the systems demands from the product. In this case, the pressure drop across the product was fed back into engine performance simulations to calculate the effect on the specific fuel consumption. The second aspect is about performing coupled simulations to predict the influence measure. In the work done (paper-B) a one way coupling was established that inputs the pressure drops form the product into turbine efficiency calculations which in turn was fed into overall engine performances.

There are three levels of coupling passes in this case which are, the overall engine, turbine module and the product (Turbine Rear Structure: TRS) that forms part of the turbine module. Performing a coupled study directly with the overall system might lead to missing important influences in the module to product associations. Therefore, the work in paper B needs to be further refined so that the product in the turbine module is studied more closely.

The only variable that is coupled in this case is just the pressure drop. Weight is an important variable of the designs and should be coupled. The extension of the studies in paper B should also include coupling the weights as well.

5.1.2 RQ2

How does the product adapt to the system?

RQ2.1: What is the internal organisation of the product and how to represent the organisation?

Paper A and C answer this question by decomposing the functions and means of the product and representing the functions and means in a graph respectively. Different sections (or regions) of the component can be thought to satisfy different functions expected of the product. In some cases, multiple sections work together to satisfy a function. Such function – means decomposition can be stored either in a configurable component framework (paper A) which enables the reuse of CCs or be represented mathematically as a graph (paper C). Mathematical representation of the product as a graph enables previously overlooked relations among functions and sections to emerge and visualise the product in a non physical manner. Thus, an integrated architecture product is represented in 'virtual modular' manner which allows to understand and exploit the organisation of the product, using measures proposed for modular architecture products.

The organisation of sections in the integrated products considered is such that certain order (spatial arrangement of different sections) is visible for a certain class of structures. For instance, for cold structure components, a vane section is mostly positioned above a bearing flange. The graph (paper C) stated earlier helps to visualise such positioning outside physical modelling possibilities. Possibilities to model entire classes of product, using their function and section descriptions are to be investigated in the future.

RQ2.2: How does internal organisation of product the affect its interaction with the system?

This question is not yet answered though the design variations in paper B can be seen as different styles of internal organisation in the product. Studies in this direction need to be performed to answer this question and will be one of the future objectives of the PhD work that is to be continued after the licentiate degree. One such study, as an extension of paper B (that explores the behaviour of a product's design in the system in which operates) with detailed product and system models, has been initiated in this direction.

5.2 Research Quality

The quality of research is often expressed in its reliability and validity. In this thesis, reliability relates to the research method, the degree to which the same results will be generated after repeated application of the method. Validity refers to how closely the results represent reality. In qualitative contexts, validity refers to the extent to which the researcher has done the right things.

5.2.1 Reliability of methods

With reference to the reliability of the methods, In case of paper A, the work is based on practices in existing literature. Paper B is conducted with existing practices of design in the industry, at GKN Aerospace. In case of paper C, the basis of creating descriptions is practices existing in the company and once the descriptions are created, the method applied is mathematical (graph theory) which ensures the repeatability of the results.

5.2.2 Validity of results

Paper A and B have undergone peer review and public presentation and defence at conferences. Paper C has only been submitted to a journal.

For paper B that predicts the influence of an aero engine component on the specific fuel consumption of the engine, the results are in line with the thumb rule measures that the engine OEM's often supply.

In case of paper C, the authors state that a design and manufacturing firm needs to identify its own vocabulary to describe and document the design. This is based on several unstructured interviews with designers at the case company as well as the author's own experience of working with the structures under consideration. Therefore, statements in paper C, even though it has recently been submitted to a journal is considered to be of appropriate validity.

5.2.3 Application of the validity square

The validity square to ascertain the quality of research was discussed in part 3.3. In this section, the validity square is applied to papers A to C.

Table 6 Validity square applied to the appended papers

	Paper A	Paper B	Paper C
(1) Accepting the construct's validity	The method used for functional decomposition is adapted from existing literature.	The methods that were used to generate the design data are based on validated design procedures at the company. The way of calculating pressure drops are consistent with method described in text books with appropriate assumptions.	Existing practice at the company is used to extract the functions and sections data about the structures. The representation of the structures is carried out using graph theory.
(2) Accepting the method's consistency	The procedure proposed has no inconsistencies.	At all stages of evaluation, all necessary data is available to each step. No inconsistencies are present.	'Function' and 'section' labels which the methods described refers to, after the initial definition is used consistently throughout. The product described does not change its design but only the manufacturing option is changed. Therefore there are no inconsistencies present.
(3) Accepting the Example problems	The structure considered for evaluation is typical of commercial aero engine static structures.	The problem considered is typical of aero engine static structure.	A pump casing is very similar to the structures that are intended to be studied. It is often a one-piece cast structure satisfying a number of functions thereby making it an integrated architecture structure.

(4) Accepting usefulness of the method for example problems	The result from this work is a procedure to decompose functions and means of an integrated architecture structure and a method to store the information. Such work is novel for integrated products.	Using the method, a quantitative measure of the component's influence on system (engine) level performance is obtained. It should be noted that models for the LP turbine need to be further refined for the results to be more accurate.	Using the method, it is possible to compare and contrast different manufacturing options for the same casing.
(5) accepting that usefulness is due to application of the method	In the industrial context (at GKN Aerospace Sweden) this method is new and no such procedure existed to generate such data.	In the context that the study was carried out, no such exercise was known to be performed, other than thumb rules from the customer. Therefore this method provides a more rigorous way of examining the system level influence than thumb rules.	In the examined context (at the case company GKN), no such method existed previously to characterise the integrated architecture structures.
(6) Accepting usefulness beyond example problems	Uncertainties related to the aspects of the method need to be considered for generalisation of the method. Further work is needed to ascertain this factor.	This aspect of the method needs to be verified and further studies are necessary with refinement of the LP turbine model.	For any integrated architecture structure, following the nomenclature that exists at a firm (provided the nomenclature is rigorous and free of conflicts), it should be possible to apply the discussed method.

6 Conclusions and Future work

This thesis was concerned with understanding the working of a product in the system in which it operates. The supplier in this case is the aerospace company GKN Aerospace Sweden AB, product refers to the static structures that the company designs and manufactures and the system is the aero engines that the structures are designed for. Additionally the internal arrangement of the structures was also a focus of the work. The thesis focussed in two directions, one about the effects on the system caused by various product designs, considering the product as a whole and the other that looks into the internal arrangement of the product.

With respect to the performance of the static structures in the system, an initial approach was examined to couple operating parameters for the product and the system. A quantitative measure was obtained to ascertain the sensitivity of the system to the design variations of the product concerned. With respect to the internal organisation of the product, a procedure was proposed to associate functional requirements with geometrical features of the product concerned. Instead of concentrating on individual parts of a product as in modular architecture, different sections (different areas or regions of the product) were thought to satisfy the functions required of the product. The product is often manufactured by splitting it into different segments and later joining them by welding. A method of associating the functional requirement of the product with different sections of it, through the manufactured segments was proposed. Different manufacturing segment concepts will then cause different patterns of associations with the functional requirements and product sections. Representing this into a graph, the architecture of the product could be observed. A graph was also generated from representing the product in CCM software. Virtual modularity was assigned to integrated products which enable application of already existing modularity measures on an integrated component.

In general, design evaluations concerning engine static structures are done in three levels, one on overall engine cycle level followed by a module level (components such as compressors or turbines) and finally the static structure level which forms part of the module. This study was done without detailed coupling at the second level (module level) which might have caused major information (boundary conditions for instance) to be missed. Besides, weight of the component which is an important consideration in engine design was also not coupled. The coupling for the considered operating variable was performed only in one way, from the product to the system.

The internal arrangement of the structure started out with the assumption that the correct listing of functions and sections are objectively performed. Besides, the sections that are defined for the products do not have a clear boundary. Depending on where the boundaries are drawn for the section, the results could vary.

Further studies for the functioning of the product in the system will concentrate on expanding the module level inputs to the analyses, and coupling weight of the component in the analyses. A study with feedback (where product design receives input from the system also) is proposed to be done in this direction.

The physical simulations for such products using computational tools (FEA or CFD) usually involve analysing the whole components. Provided a systematic function-section mapping is performed, the functional decomposition might enable an effective physical domain decomposition enabling distributed and efficient analyses. Additionally, the organisation of design information is expected to open up opportunities for comparison of alternative product architectures based on the available manufacturing options. Assessing the suitability of a certain manufacturing split is also a direction that can be pursed. The research question RQ2.2 regarding how the internal organisation affects external performance of the product is still to be answered. This will also be taken up during the continued studies within this project.

REFERENCES

ANDERSSON, F., NILSSON, P. & JOHANNESSON, H. Computer based requirements and concept modelling-information gathering and classification. 12th International Conference on Design Theory and Methodology. 2000 ASME International Design Engineering Technical Conferences, 2000.

BLESSING, L. T. M. & CHAKRABARTI, A. 2009. *DRM, a design research methodology,* Dordrecht;London;, Springer.

BOEING. 2015. *Traffic and Market Outlook* [Online]. Available: http://www.boeing.com/commercial/market/long-term-market/traffic-and-market-outlook/ [Accessed 28 April 2016].

BYTHEWAY, C. W. 2007. *FAST Creativity & Innovation: Rapidly Improving Processes, Product Development and Solving Complex Problems,* J.Ross Publishing.

CHAKRABARTI, A. & BLIGH, T. P. 1994. An approach to functional synthesis of solutions in mechanical conceptual design. Part I: Introduction and knowledge representation. *Research in Engineering Design,* 6**,** 127-141.

CHARTRAND, G. & LESNIAK, L. 1996. *Graphs & digraphs (3.rd ed.),* Boca Raton, Chapman & Hall.

CLEAN SKY. 2016. *SAGE 2 – Geared Open Rotor* [Online]. Available: http://www.cleansky.eu/content/page/sage-2-%E2%80%93-geared-open-rotor [Accessed 28 April 2016].

CRESCENDO. 2009. *Collaborative & Robust Engineering using Simulation Capability Enabling Next Design Optimisation* [Online]. Available: http://cordis.europa.eu/project/rcn/93958_en.html [Accessed 20 April 2016].

DÉPINCÉ, P., GUÉDAS, B. & PICARD, J. 2007. Multidisciplinary and multiobjective optimization: Comparison of several methods. *7th World Congress on Structural and Multidisciplinary Optimization.* Seoul, South Korea.

DIXON, J. R. 1995. Knowledge-based systems for design. *Journal of Mechanical Design,* 117**,** S11.

ECKERT, C. M., CLARKSON, P. J. & STACEY, M. K. The Spiral of Applied Research – A Methodological View on Integrated Design Research. The 14th International Conference on Engineering Design, ICED 03, 2003 Stockholm. Paper No. 1139.

EPPINGER, S. D. A Planning Method for Integration of Large-Scale Engineering Systems. International Conference on Engineering Design, 1997 Tampere, Finland. 199-204.

FLOWSERVE INC HPX API 610 (OH2) Centerline Mounted Pump

GE AVIATION. 2011. GEnx Overview | GEnx Engine Family | Commercial Jet Engines | GE Aviation Available from: https://www.youtube.com/watch?v=S1ahHWXGx5Y [Accessed 25 April 2016].

GKN AEROSPACE. 2014. *Presentations* [Online]. Available: http://www.gkn.com/aerospace/media/resources/Presentations/GKN-Aerospace-Fan-and-Turbine-Engine-Structures.pdf [Accessed 19 April 2016].

GOLDREI, D. 1996 *Classic set theory : a guided independent study,* London, Chapman & Hall.

HAGUE, D. C. 2001. *Description of a turbofan engine product development process,* c2001.

HANSEN, C. T. & ANDREASEN, M. M. 2002. Two approaches to synthesis based on the domain theory. *In:* CHAKRABARTI, A. (ed.) *Engineering Design Synthesis: Understanding, Approaches and Tools.* London: Springer London.

HOLTTA-OTTO, K. & DE WECK, O. 2007. Degree of Modularity in Engineering Systems and Products with Technical and Business Constraints. *Concurrent Engineering,* 15**,** 113-126.

IMPACT-AE. 2013. *Intelligent Design Methodologies for Low Pollutant Combustors for Aero-Engines* [Online]. Available: http://www.impact-ae.eu/ [Accessed 20 April 2016].

JARRETT, J. P., DAWES, W. N. & CLARKSON, P. J. 2007. An Approach to Integrated Multi-Disciplinary Turbomachinery Design. *Journal of Turbomachinery,* 129**,** 488.

JOHANNESSON, H. & CLAESSON, A. 2005. Systematic product platform design: a combined function-means and parametric modeling approach. *Journal of Engineering Design,* 16**,** 25-43.

KIM, H. M., RIDEOUT, D. G., PAPALAMBROS, P. Y. & STEIN, J. L. 2003. Analytical Target Cascading in Automotive Vehicle Design. *Journal of Mechanical Design,* 125**,** 481-489.

KUSIAK, A. & LARSON, N. 1995. Decomposition and Representation Methods in Mechanical Design. *Journal of Mechanical Design,* 117(B)**,** 17-24.

LEVANDOWSKI, C. E. 2014. *Platform lifecycle support using set-based concurrent engineering.* PhD, Chalmers University of Technology.

MICHAELIS, M. T. 2013. *Co-Development of Products and Manufacturing Systems Using Integrated Platform Models.* PhD, Chalmers University of Technology, Göteborg.

PEDERSEN, K., EMBLEMSVAG, J., BAILEY, R., ALLEN, J. K. & MISTREE, F. Validating design methods and research: the validation square. ASME Design Theory and Methodology Conference, 2000.

RAJA, V. & ISAKSSON, O. Generic Functional Decomposition of an Integrated Jet Engine Mechanical Sub System Using a Configurable Component Approach. *In:* RICHARD CURRAN, N. W., MILTON BORSATO, JOSIP STJEPANDIĆ, WIM J.C. VERHAGEN, ed., 2015 Delft, Netherlands. IOS Press, 337-346.

REINMAN, G., AYER, T., DAVAN, T., DEVORE, M., FINLEY, S., GLANOVSKY, J., GRAY, L., HALL, B., JONES, C., LEARNED, A., MESAROS, E., MORRIS, R., PINERO, S., RUSSO, R., STEARNS, E., TEICHOLZ, M., TESLIK-WELZ, W. & YUDICHAK, D. 2012. Design for Variation. *Quality Engineering,* 24**,** 317-345.

ROLLS-ROYCE PLC. 2014. *Trent 1000 Info Graphic* [Online]. Available: http://www.rolls-royce.com/site-services/images/trent-1000-infographic.aspx [Accessed 25 June 2015].

SAMUELSSON, S. 2016. *Challenges in aero engine performance modeling.* Engineering Licentiate Licentiate Thesis, Chalmers University of Technology.

SANDBERG, M., TYAPIN, I., KOKKOLARAS, M., ISAKSSON, O., AIDANPAA, J. O. & LARSSON, T. 2011. A Knowledge-based Master-model Approach with Application to Rotating Machinery Design. *Concurrent Engineering,* 19**,** 295-305.

STONE, R. B. & WOOD, K. L. 1999. Development of a Functional Basis for Design *Journal of Mechanical Design,* 122**,** 359-370.

TOICA. 2013. *Thermal Overall Integrated Conception of Aircraft* [Online]. Available: http://www.toica-fp7.eu/ [Accessed 20 April 2016].

TRANSPORT - RESEARCH & INNOVATION EUROPEAN COMMISSION. 2012. *VITAL Environmentally Friendly Aero-Engine* [Online]. Available: http://ec.europa.eu/research/transport/projects/items/vital_en.htm.

ULLMAN, D. G. 2010. *The Mechanical design process,* Boston, McGraw-Hill.

ULRICH, K. 1995. The role of product architecture in the manufacturing firm. *Research Policy*, 24**,** 419-440.

ULRICH, K. T. & EPPINGER, S. D. 1995. *Product Design and Development (International Editions 1995),* Singapore, McGraw-Hill, Inc.

ULRICH, K. T. & SEERING, W. P. 1990. Function Sharing in Mechanical Design. *Design Studies,* Volume 11**,** Pages 223-234.

UMEDA, Y., ISHII, M., YOSHIOKA, M., SHIMOMURA, Y. & TOMIYAMA, T. 1996. Supporting conceptual design based on the function-behavior-state modeler. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM,* 10**,** 275-288.

VAN ECK, D., MCADAMS, D. A., VERMAAS, P. E. & ASME 2008. *Functional decomposition in engineering: A survey*.

VAN TOOREN, M., NAWIJN, M., BERENDS, J. & SCHUT, E. Aircraft design support using knowledge engineering and optimisation techniques. 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 13th AIAA/ASME/AHS Adaptive Structures Conference, 2005. 18-21.

VINNOVA-NFFP6. 2013. *Konstruktion för Prestanda - avancerad motorarkitektur och integration* [Online]. VINNOVA. Available: http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2012-03138/Konstruktion-for-Prestanda---avancerad-motorarkitektur-och-integration/ [Accessed 23 June 2016].